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Sediment yields and sediment budgets of community water supply watersheds in southeastern British Columbia.

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Abstract: Over the past 10 years, the B.C. Forest Service has measured sediment concentration and turbidity on a number of creeks in the Kootenay region of British Columbia, which are used for community or domestic water supply. This paper summarizes the results of measurements on 11 forested watersheds. Some of them have streamflow stations, so that suspended sediment data collected for water quality purposes can be converted to sediment yield. Reasonable estimates of discharge and yield can be made for the remaining creeks. Both undeveloped and developed watersheds are included. For most watersheds, annual background suspended sediment yields are comparable to or slightly higher than the range of published Water Survey of Canada results for small forested watersheds (about 3 to 10 $t/km^2/y$). These yields are lower than for most watersheds in British Columbia. Streams with low sediment yield have been chosen by communities as water sources because they provide good quality water. In some watersheds with forestry development, sediment yield is significantly greater than background levels, due mainly to erosion from logging roads. However, in most cases, the amount of sediment is still within generally accepted water quality guidelines. In rare cases, landslides caused by forest roads have resulted in very large increases in sediment yield.

Introduction

In the mountainous Kootenay region of southeastern British Columbia, most communities and rural residents rely on surface water sources for their drinking water. The source watersheds drain the mainly forested mountains adjacent to the populated main valleys. The climate of the region is predominantly humid, with a deep winter snowpack and reliable rainfall in the summer. Furthermore, the level of geomorphic activity in most forested watersheds is low, and the creeks have relatively low sediment yields. Therefore, most populated areas have a nearby source of reliable, high quality water, which can be exploited at very low cost, without storage, and which requires little or no treatment.

Almost all the community and domestic water supply watersheds in the region are predominantly within the Crown-owned provincial forest. The government's policy is that the forest is available for commercial timber harvesting on a sustained-yield basis, as in the provincial forest throughout British Columbia. An important and contentious issue in the region is whether forest development causes an increase in the sediment supply to streams, and if so, whether this results in impacts on water quality.

For the last 20 years, the British Columbia Ministry of Forests has been monitoring suspended sediment in a number of creeks which are used for community and domestic water supply in the region. This monitoring has been mostly on a piecemeal basis, usually in response to local concern about existing or proposed forest development in a watershed. In about 1993, a more systematic research program began, with the main objectives of measuring typical background (or natural) values of sediment concentration and other relevant water quality parameters, investigating the extent to which forest development affects water quality, and determining what forest practices are responsible for water quality impacts and how these impacts can be minimized.

In theory, there is no mechanism by which road-building and logging can reduce the sediment supply; it can only increase it. The relevant question is, is the increase in sediment significant? A related question is, can we measure the increase, and assess its significance, both at a research and an operational level?

The present research project began in 1993 to 1996 with monitoring turbidity in the community watersheds of the City of Nelson, and of Erickson (near Creston). For various reasons, neither of these locations proved suitable for conducting a long-term research project on the impacts of forest development on water quality. In 1997, we undertook a project whereby water was systematically sampled on a number of different creeks in the region which are used for community and domestic water supply. The results of this project are reported in this paper.

(Administratively, these water sources fall into two categories: community watersheds, which are designated watersheds supplying a community water system; and domestic watersheds, which have one or more individual domestic water licenses but have no official designation. Usually but not always, a community watershed supplies a city, town, or rural "improvement district" with a single treatment and distribution system, while a domestic watershed supplies have a number of

water intakes supplying individual residents or unorganized groups of water users, with rudimentary or no treatment facilities. Under the Forest Practices Code, community watersheds are subject to some more stringent regulations governing planning and timber harvesting.)

The only previous systematic information on sediment yields in the region is the record of the Water Survey of Canada (WSC), which collected sediment data on six creeks for varying periods during the years 1967-92. These data were compiled, for all of British Columbia, by Church et al. (1989). The data for the stations in this region are summarized in Table 1. Four of these stations are on community watersheds. It is significant that these have the lowest sediment yields of all the stations in British Columbia, with the exception of several which are controlled by large lakes or reservoirs. Although many high sediment yielding streams exist in the region, it is our observation that (not surprisingly) creeks with low sediment yield are preferentially selected for water supply, due to their high water quality.

In previous regional analyses of sediment yield in the western Canadian cordillera, it has been found that in most river systems, sediment yield increases downstream, with low sediment yield in small headwater basins, and increased yield downstream as rivers erode Pleistocene glacial deposits which fill the main valleys (Slaymaker, 1986; Church and Slaymaker, 1989). In the Kootenay region, in most (but not all) small upland watersheds, deep glacial deposits are scarce; however, they are abundant in the low-gradient river valleys. According to this model, one would most frequently expect to find high-quality water (with respect to sediment concentration) in the small, upland watersheds, and furthermore, in watersheds where deep glacial deposits border the main channel, sediment sources should be more abundant and sediment concentration higher. This is consistent with local experience.

Objectives and methodology

The specific objectives of this study were:

- To sample a representative selection of streams used for community and domestic water supply throughout the region;
- To measure the typical range of background turbidity and suspended sediment for undeveloped watersheds;
- To make some preliminary conclusions on the effects of forest development on turbidity and suspended sediment yield;
- To investigate the influence of watershed geology on sediment yield;
- To select a suitable watershed in which to conduct a long-term research project on the impacts of forest development on water quality.

With respect to the fourth objective, previous water sampling in the region had concentrated on watersheds in the Nelson area which are underlain mainly by granitic rock and which have coarse, sandy soils. Through practical experience in the region, we believe that watersheds with finer-textured bedrock and soils behave differently, especially with respect to the effects of erosion of forest roads on suspended sediment yield. Therefore, we wanted to include watersheds with a representative cross-section of geology in the study.

We selected 11 watersheds for study. The one common attribute was that all watersheds are used for community or domestic water supply, and are considered by the Ministry of Forests to be "important" watersheds in that their value for water use is likely to be a significant constraint in forest development planning. The total number was limited by the resources available, both finances and staff. We attempted to include watersheds which were representative of the range of geology and land use in the region. To a large extent, the selection of watersheds was opportunistic, based on the availability of communities which were interested in participating in the study, or of individuals willing to collect samples as volunteers or at a nominal cost. Ideally, if resources were not limiting, we would have preferred to have a larger number, objectively chosen to provide a sample of developed and undisturbed watersheds. The location of the watersheds is shown in Figure 1. Their characteristics are described in the following section and in Table 2.

The general approach was to collect and analyze daily water samples on each stream, using a consistent sampling design. This was to sample daily during the spring freshet period, and approximately twice per week at other times, with additional samples collected during major hydrologic events. The period of sampling was April through September. As standard procedure, whenever feasible samples were collected in the late afternoon, which is the time of highest discharge during snowmelt dominated periods.

Samples were analysed for turbidity in our lab, using a Hach 2100N turbidity meter. Samples exceeding 1 NTU, and all samples during the major runoff events, were analysed for suspended sediment concentration at the Environment Canada lab in Edmonton, Alberta.

For the purpose of calculating sediment budgets, sediment concentration is used. However, for water quality purposes, turbidity is usually the parameter of interest. Generally accepted water quality standards in British Columbia are 1 NTU for water entering a distribution system, and 5 NTU for water at the source. Above about 20 NTU, water becomes visibly cloudy, and is considered aesthetically unsuitable for drinking. Turbidity and sediment concentration in streams are closely related, as almost all turbidity is due to sediment (the exception being water with a high content of algae or other micro-organisms). Sediment is considered to include non-living organic material, as well as mineral material; for example, decayed leaves, humus, and forest floor litter, which are important components of sediment in forest environments.

An automatic recording turbidity meter was installed at one of the sites (Hill Creek). Also, turbidity meters are being used in a long-term sediment budget study, which is being conducted at Redfish and Laird Creeks in the West Arm Demonstration Forest near Nelson. The results of this study, and the use of recording turbidity meters in general, are reported elsewhere (Jordan and Commandeur, 1998). Summary sediment yield data, based on samples, is included for Redfish and Laird Creeks in the results of the present study. On these creeks, we had automatic pump samplers collecting three samples per day, in addition to the daily manual sample.

For several of the creeks, discharge is measured by the WSC. For other stations, discharge for the period of the study was estimated by using the record of a nearby WSC station with a similar elevation distribution. If the gauged and ungauged watersheds were sufficiently similar, the flow

data were transformed by simply using the ratio of their drainage areas. In some cases, the records of two nearby stations were combined to give a better estimate. For example, for Fortynine Creek, two nearby gauged streams have a higher and a lower elevation distribution, and these were combined with appropriate weightings to give an elevation distribution reasonably close to that of Fortynine Creek. A more rigorous hydrologic modeling procedure would probably give a better estimate; however, this simple procedure was considered sufficient for the purposes of this study. At Hill Creek, we installed a water level recorder, and did three stream gauging measurements to establish a rating curve. However, insufficient measurements were done at high flow, and we believe that high flows were underestimated.

The data were analysed according to the following procedure. For each creek, daily flow data, and turbidity and suspended sediment concentration, were tabulated. The suspended sediment load can be calculated for each day with a sample, as the product of concentration and discharge, assuming that the daily sample is representative of concentration for the entire day.

For each station, suspended sediment concentration and turbidity were plotted, and a relation was derived by regression. An example is shown in Figure 2. A double logarithmic (log-log) relation was used as the data appear reasonably close to log-normally distributed. The logarithm of turbidity minus 0.2 NTU was used, because measured turbidity values converge on this value (the turbidity of filtered water in our lab is about 0.2 NTU), and if this correction is not made, the cluster of points tends to be curved at its lower end. (A basic property of log-log relations is that they are assumed to approach the point [0,0] at their lower limit.) For samples for which concentration was not measured, it was estimated from the regression relation. Almost always, samples for which concentration was estimated had turbidity lower than 1 NTU. Thus, their contribution to the total sediment yield was minor.

Inevitably, samples were missed on some days. Also, during low flow seasons, samples were only collected every several days. To estimate the missing data, relations were plotted between suspended sediment and discharge. An example of such a relation is shown in Figure 3. Invariably, these relations show large scatter and strong seasonal hysteresis. This is not unexpected, because during runoff events, local sediment sources are likely to vary greatly throughout the watershed and from day to day. The seasonal hysteresis occurs because, during the first large rise of the creek, sediment which has been stored along the creek banks during the preceding 9 months is entrained. This includes sediment which has been deposited in the streambank region by mass movement processes, snow avalanche debris, and decayed leaves which fell in the channel area the previous autumn. (The latter is a very significant contributor to turbidity and sediment load in these low-sediment-yield, forested watersheds.) To estimate the sediment load on missing days, lines were drawn by eye through the early-season and late-season clusters of points. The scatter in these relations is a major source of error in the estimated sediment loads.

The results of these calculations were summed for the April-September period, and expressed as a suspended sediment yield in tonnes/km^2.

Watershed descriptions

A summary of the characteristics of each watershed is given in Table 2. Some additional information on some watersheds follows.

Redfish and Laird Creeks: These watersheds are the location of a sediment budget study which began in 1993. Redfish Creek has had forest development since the 1960s, while Laird Creek is the undeveloped control watershed.

Anderson Creek: Although it has no roads or logging from the modern era, there was considerable logging in the early part of the century, probably mostly in the 1930s and earlier. Although any sediment sources from this logging are probably no longer active, logging may have created disturbance in the riparian area which has not fully recovered. During the 1997 spring runoff, which was about a 20-year flood, an unusually large amount of bedload moved in the channel.

Fortynine Creek: In 1996, a large landslide occurred below a logging road, and moved as a debris flow down 2 km of a tributary channel to the creek. The volume of this unusual event is estimated at 8000 m^3. Water samples are collected to monitor recovery of water quality from the event, and the success of rehabilitation efforts.

Hill Creek: This is the site of a fish hatchery and artificial spawning channel, and has only minor domestic water use. Its watershed is underlain by weak metasedimentary rocks, and has steep slopes and abundant alpine areas and avalanche tracks (similar to Meadow and John Creeks, reported by Church et al., 1989).

Arrow Creek: Although it provides drinking water to a community, most of the water from the waterworks system is used for irrigation of orchards and vegetable farms, and the water also supplies British Columbia's largest brewery.

Joseph and Gold Creeks: These watersheds have fairly extensive old selective logging, from the 1950s and earlier. Any sediment sources from this logging have probably recovered, although there may be some unrecovered channel disturbance. The creeks were sampled by City of Cranbrook employees. Unfortunately their sampling program did not begin early enough in the spring, and so the first main hydrograph rise was missed.

Hospital Creek: This creek is underlain by very weak and erodible sedimentary rocks, typical of the western ranges of the Rocky Mountains. Debris flows originating on bare alpine ridges are common in its watershed.

The forestry development noted on Table 2 refers to roads and logging from the "modern" era of clearcut logging and logging truck roads, beginning in about the 1960s. In addition, most watersheds have old roads from earlier, less intensive logging, as well as some fire roads and, in some cases, old mining roads. In general, the forests have substantially regrown from this early logging, and old roads and skid trails have become vegetated and are unlikely to still be active sediment sources.

The amounts of logged area and roads were estimated, in most cases, from forest cover maps. The figures should be considered approximate, as the maps are not entirely up to date, and do not reliably distinguish active roads from old roads. The figures from Ladybird and Deer Creeks were obtained from recent watershed assessments and were prepared using GIS methods; they are more precise.

Alpine areas were estimated from 1:50,000 topographic maps on which timberline is marked. These areas refer to land completely above treeline; alpine areas (including sparse "alpine forest") as shown on forest cover maps would be considerably more extensive.

Bedrock geology is divided into four categories. *Coarse Granitic* refers to the Nelson Batholith and related Mesozoic intrusions; glacial till and derived soil is mostly coarse and sandy. *Medium Sedimentary* includes Precambrian rocks of the Purcell Group, which are mostly relatively unmetamorphosed sandstones and siltstones; soils tend to be dominated by silt and fine sand. *Medium Metamorphic* refers to Mesozoic metavolcanic and metasedimentary rocks (and minor intrusive rocks) of the West Kootenays; soils are mainly sandy to silty. *Fine Sedimentary* includes mainly pelitic (shaley) rocks of the Paleozoic to Mesozoic Kootenay Arc (altered argillites and slates, and some metavolcanic rocks), and in the Rocky Mountains, lower Paleozoic micaceous phyllite, shale, and slate. Soils tend to be silty to clayey, and colluvial activity is extensive on steep slopes.

Results and discussion

As examples, daily stream discharge, turbidity, and suspended sediment yield are plotted for two creeks, Arrow Creek and Hospital Creek, on Figures 4 and 5. As expected, turbidity and sediment yield are highly correlated with discharge. In 1997, throughout the region, the first main runoff event (May 8-17) was caused by a period of hot sunny weather with rapid snowmelt, and the second (May 28-June 18) was caused by a period of cooler, rainy weather with high streamflow due to rain combined with melting of the remaining snowpack.

On Hospital Creek, the September turbidity events were due to localized thunderstorms, which apparently were not experienced in the nearly Split Creek which was used for estimating discharge. Therefore sediment yield for these events is underestimated.

The results for all 11 creeks, expressed as total suspended sediment load in tonnes/km^2, are summarized in Table 3. The column giving "% of sediment load measured" is the percentage of the total load obtained from actual measurements of sediment concentration, not estimates. It is a measure of the reliability of the calculated total and the adequacy of sampling.

The totals are a reasonable approximation of total annual sediment yield. During the fall-winter period (October-March), sediment yield is usually very minor. For the six Kootenay creeks reported in Church et al. (1989), 90 to 97% of the annual yield occurred in the three spring months of April, May, and June.

In general, the results show that sediment yield has apparent but inconclusive correlations with geology, and with the presence or absence of forest development. The three granitic basins have

the lowest sediment yields, but there is no obvious difference amongst the other three geologic categories. For the two adjacent pairs of developed and (relatively) undeveloped watersheds, Redfish-Laird and Gold-Joseph, the developed watershed has a higher sediment yield. For Redfish and Laird Creeks, this has been examined in greater detail (Jordan and Commandeur, 1998), and found to be mainly due to erosion from logging roads. However, throughout the region there does not appear to be a consistent trend to greater sediment yield from developed watersheds (with the exception of Fortynine Creek, discussed below). The sample of streams in this study, however, is too small to do a statistical analysis or reach any definite conclusions.

To further explore the effect of watershed geology, the regression relations between turbidity and suspended sediment concentration for all creeks are shown on Figure 6. One would expect that for finer-textured sediment, the turbidity should be higher for a given sediment concentration, than for coarser-textured sediment. This is because fine particles (e.g. clay) are much more numerous than coarse particles (e.g. sand) and therefore scatter the light more. However, with the one exception of Hospital Creek, the lines on Figure 6 do not follow this trend. Also on the figure are shown two lines for artificial samples as measured in our lab, one for fine-textured sediment (clayey silt) obtained from a glaciolacustrine deposit, and one for coarse-textured sediment (sandy silt) sieved from a sample of sandy glacial till. These two samples show the expected relation with texture, and also, they bracket most of the lines for the water samples from creeks.

In most cases, we were not able to correlate sediment yields with any specific sediment source in the watersheds. Most watersheds have numerous small or diffuse sources, from logging roads or from natural geomorphic sources such as bank erosion. In Deer Creek, and to a lesser extent Gold Creek, there are extensive glaciofluvial deposits bordering the lower reaches of the creeks, so there may be greater opportunity for bank erosion to contribute sediment. In both these watersheds, logging roads have been built through these deposits, resulting in several small landslides (Deer Creek) and areas of road cut erosion (Gold Creek) close to the creek channels. In Redfish, Ladybird, Deer, Hill, and Hospital Creek, there have been several (4 to 10 documented) relatively small (less than several 100 m^3) landslides over the last 10 to 20 years, but none of these occurred in 1997.

Fortynine Creek is a significant exception to the above results. It has by far the highest sediment yield of the 11 creeks (Figure 7). In 1996, a very large landslide occurred in this watershed (as noted above). A tributary channel was severely disturbed by this event for two kilometres, leaving the banks unvegetated and exposed to erosion. The peak stream discharge in 1997 was higher than in 1996, and extensive bank erosion, channel migration, and entrainment of stored debris flow deposits occurred along the length of this tributary. Also, some enlargement of the original landslide took place at the same time. In response to complaints from water users, the senior author made an inspection by helicopter of the watershed, on what turned out to be the day of peak sediment discharge. He was able to observe the erosion taking place along the channel, resulting in the water becoming visibly more turbid as it progressed downstream, and also to observe extremely turbid water entering the Kootenay River at the creek mouth. This confirms the water sample data collected at close to the same time. However, the total calculated sediment yield for that day of 3200 tonnes may not be reasonable, as it is almost as great as the

amount of fine sediment in the original landslide. It is likely that the high sediment concentration values apply only to a few hours of the several days of this erosion event, not to the entire 24 hour period, and so the total sediment yield for the creek may be a considerable overestimate. Although this event is an extreme example, not representative of the regional results, it demonstrates the fact that if a large landslide occurs in a watershed, it is likely to dominate the sediment regime for that year and possibly several years following.

For Redfish, Laird, and Arrow Creeks, sediment yield data are available for additional years (Table 4). These data show that, for the 5-year record on Redfish Creek, 1997 had the highest total runoff and peak discharge. Both creeks had higher than average sediment yield in 1997, and Arrow Creek also had a higher yield in 1997 than 1996. It is probably reasonable to extrapolate this trend to the other streams, and conclude that 1997 had higher sediment yields than the 5-year average. Most of the creeks, including Anderson and Arrow, had higher sediment yields in 1997 than the yields reported for these and similar creeks by Church et al. (1989). This may be explained by the higher than average streamflow, and correspondingly higher erosion within the watersheds, in 1997. In 1997, there was a near-record snowpack at low elevations, as well as rapid snowmelt and some heavy spring rainstorms. Some streams experienced unusually high peak discharges, especially creeks with a low elevation distribution and those in the southern part of the region. The most affected of those in this study were Anderson, Arrow, Gold, and Joseph Creeks.

Considering water quality, the turbidity data show that (Table 3), for all streams except Fortynine Creek and Hospital Creek, turbidity exceeds the 5 NTU standard for fewer than 14 days each year. This is consistent with our observations (which are unsupported by measurements) on many creeks throughout the region.

A convenient way to express the magnitude-frequency relation of sediment yield is a cumulative curve of daily yield against either time or discharge. Such a plot is shown in Figure 8, for Arrow Creek. In this example, 50% of the annual sediment yield occurred on only 4 days, and 90% occurred on 18 days. This pattern is typical of the snowmelt-dominated small streams in the region. A similar demonstration of the trend for most of the sediment yield (and turbidity) to occur on only a few days, more useful for water quality purposes, is to plot a histogram of concentration (Figure 9).

Conclusions

The data from the four largely undeveloped watersheds sampled in 1997 are consistent with, although somewhat higher than, previously reported WSC data in Church et al. (1989). Sediment yields on typical streams used for community and domestic water supply are relatively low, compared to average yields for larger streams throughout British Columbia. Turbidity on most creeks is lower than the standard of 5 NTU on all but a few days of the spring freshet.

There appears to be some relation between higher sediment yield and forest development, although the number of creeks sampled is not sufficient to make a definite conclusion. Also there is some apparent relation with geology, with watersheds underlain by granitic rocks having the lowest sediment yields.

Turbidity-concentration relations are reasonably linear and somewhat consistent amongst watersheds, regardless of geology. However, concentration-discharge relations have great scatter and pronounced seasonal hysteresis, precluding the use of sediment rating curves for accurately estimating sediment yield.

Large landslides are rare in the sampled watersheds and in similar watersheds throughout the region, but when they occur, they greatly increase sediment yield and can dominate the sediment regime for several years.

Significant sources of error in this study are the estimation of discharge for ungauged creeks, estimation of sediment concentration for "missing" days from sediment rating curves, and the assumption that a single sample is representative of concentration for the entire day.

Daily manual sampling is an effective and economical means of monitoring water quality and calculating sediment yield during the spring freshet. However, daily sampling is not likely to be representative of short-duration events in small watersheds.

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Table 1. Published sediment data for creeks in the Kootenay region of British Columbia.

Creek	Station number	Drainage area (km^2)	Period of record	Mean annual [3] yield ($T/km^2/y$)	Range of annual [3] yields ($T/km^2/y$)
Arrow Creek [1]	08NH084	78.7	1979-85	8	3 - 11
Duck Creek [1]	08NH016	57	1979-85	7	3 - 11
Five Mile Creek [1]	08NJ168	47.5	1983-92	5	3 - 12
Anderson Creek [1]	08NJ130	9.1	1983-85	3	1 - 5
Meadow Creek [2]	08NH124	62.7	1967-73	29	8 - 49
John Creek [2]	08NH125	34.7	1967-73	69	12 - 140

1 Community watershed

2 Erodible geology, extensive natural sediment sources

3 Yields are given to the nearest whole $T/km^2/y$ due to imprecision in the original data, and to avoid rounding errors in converting from the original units given.

Source: Church et al (1989), supplemented with Water Survey of Canada data published since then.

Table 2. Summary of watershed characteristics.

Watershed	Gauging station	Area (km^2)	Elevation range (m)	Alpine area	Area [5] logged	Road length (km/km^2) [5]	Geology	Water licenses
Redfish	08NJ061	26.2	700-2370	6%	10%	0.7	coarse granitic	20 domestic
Laird	08NJ019	15.0	790-2360	9%	<1%	0	coarse granitic	64 domestic
Anderson	08NJ130	9.07	700-2030	0	0	0	medium metamorphic	community [1]
Fortynine	estimated	25.6	730-2220	4%	16%	1.4	medium metamorphic	41 domestic
Ladybird	estimated	158	600-2550	9%	8%	0.7	coarse granitic	community [2]
Deer	08NE087	80.5	470-2350	3%	12%	0.9	medium metamorphic	67 domestic
Hill	measured	27.5	530-2440	15%	3%	0.4	fine sedimentary	fish hatchery; 2 domestic
Arrow	08NH084	78.7	760-2200	<1%	0	0.1	medium sedimentary	community [3]
Joseph	estimated	35.3	1100-2150	<1%	1%	0.3	medium sedimentary	community [4]
Gold	estimated	92	1340-2170	<1%	13%	0.7	medium sedimentary	community [4]
Hospital	estimated	25.1	1040-2560	20%	7%	0.6	fine sedimentary	8 domestic

1 City of Nelson

2 Robson-Raspberry Improvement District

3 Erickson Improvement District

4 City of Cranbrook

5 Excludes minor selective logging before about 1960. Most watersheds have some old logging, mining, or fire roads in addition to those included. Road length is a rough estimate only.

Table 3. Summary of results.

Watershed	Total suspended sediment load (tonnes/km^2)	% of sediment load measured	Maximum sampled turbidity (NTU)	Days with [1] turbidity > 5 NTU	Remarks
Redfish	11	78%	25	4	
Laird	5	75%	28	3	
Anderson	38	99%	101	8	2nd highest flood in 36 y
Fortynine	290	100%	3350	39	Disturbed by large landslide in 1996
Ladybird	5	51%	13	n/a	
Deer	10	61%	16	n/a	
Hill	12	75%	27	8	Discharge may be under-estimated at high flows
Arrow	16	88%	70	13	
Joseph	12	34%	18	n/a	Insufficient sampling
Gold	20	34%	13	n/a	Insufficient sampling
Hospital	28	97%	255	36	Extensive natural sediment sources

1 "n/a" means insufficient samples collected. All or part of the peak turbidity event may have been missed.

Table 4. Hydrologic and sediment yield data by year.

Hydrologic summary:	1993	1994	1995	1996	1997
Redfish - total Apr-Sept runoff (mm)	600	695	703	1075	1250
Redfish - peak daily discharge (m3/s)	5.28	4.79	5.45	6.51	8.94
Sediment yield: Apr-Sept (t/km2)					
Redfish	9	2	5	10	11
Laird	4	1	4	8	5
Arrow				11	16

Note: 1993-95 sediment yield was calculated by a different method. Missing data in early spring and late summer were not estimated; therefore total seasonal yield may be slightly underestimated.

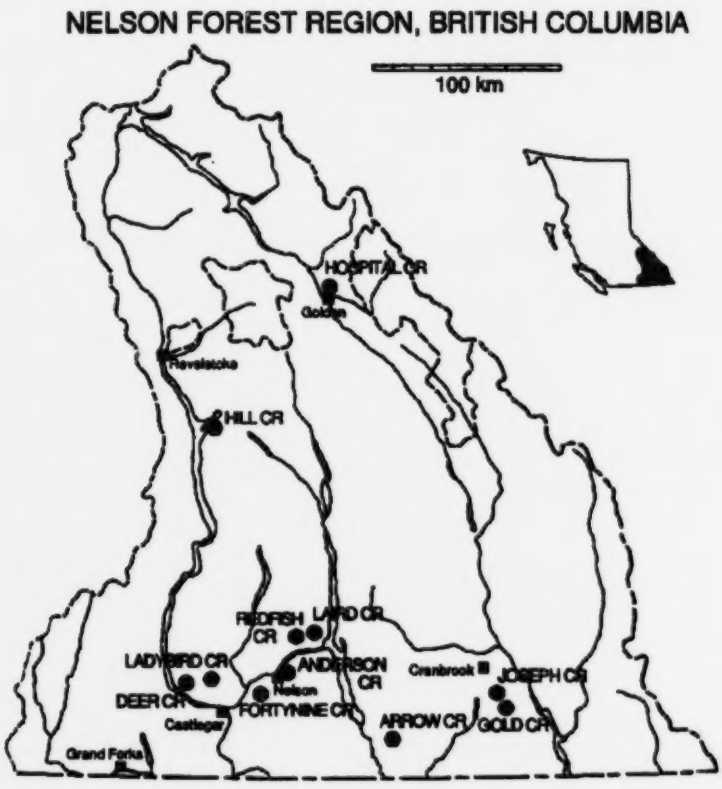

Figure 1. Location map.

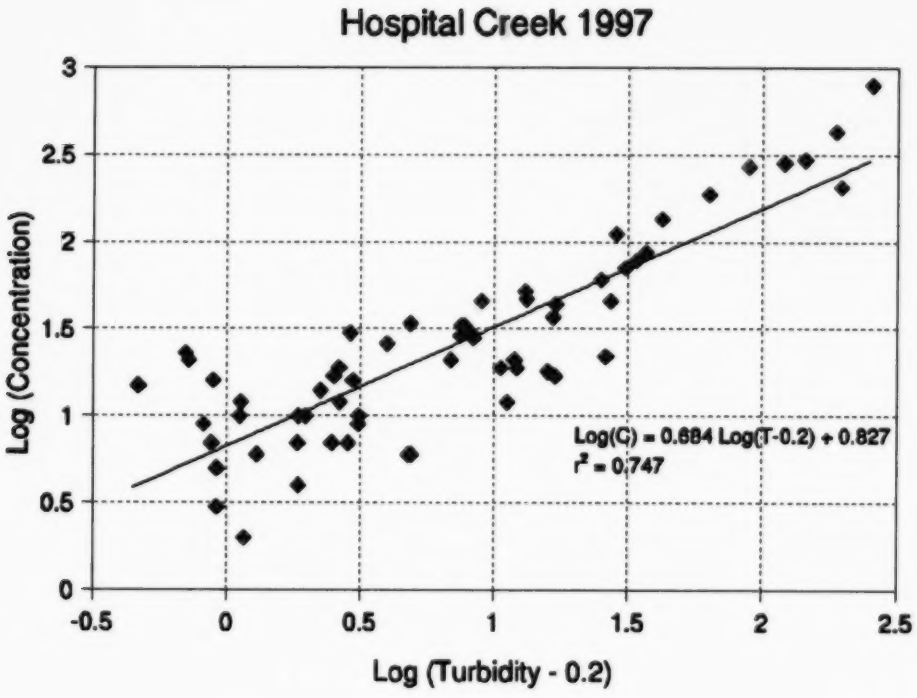

Figure 2. Example of turbidity-concentration relation.

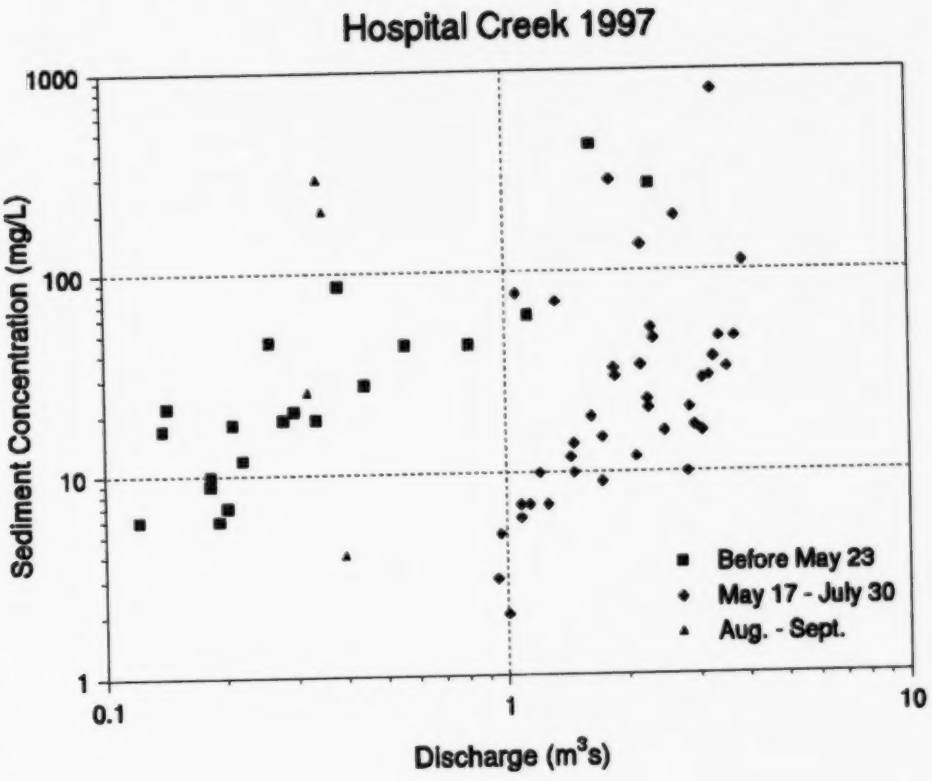

Figure 3. Example of discharge-concentration relation, illustrating hysteresis.

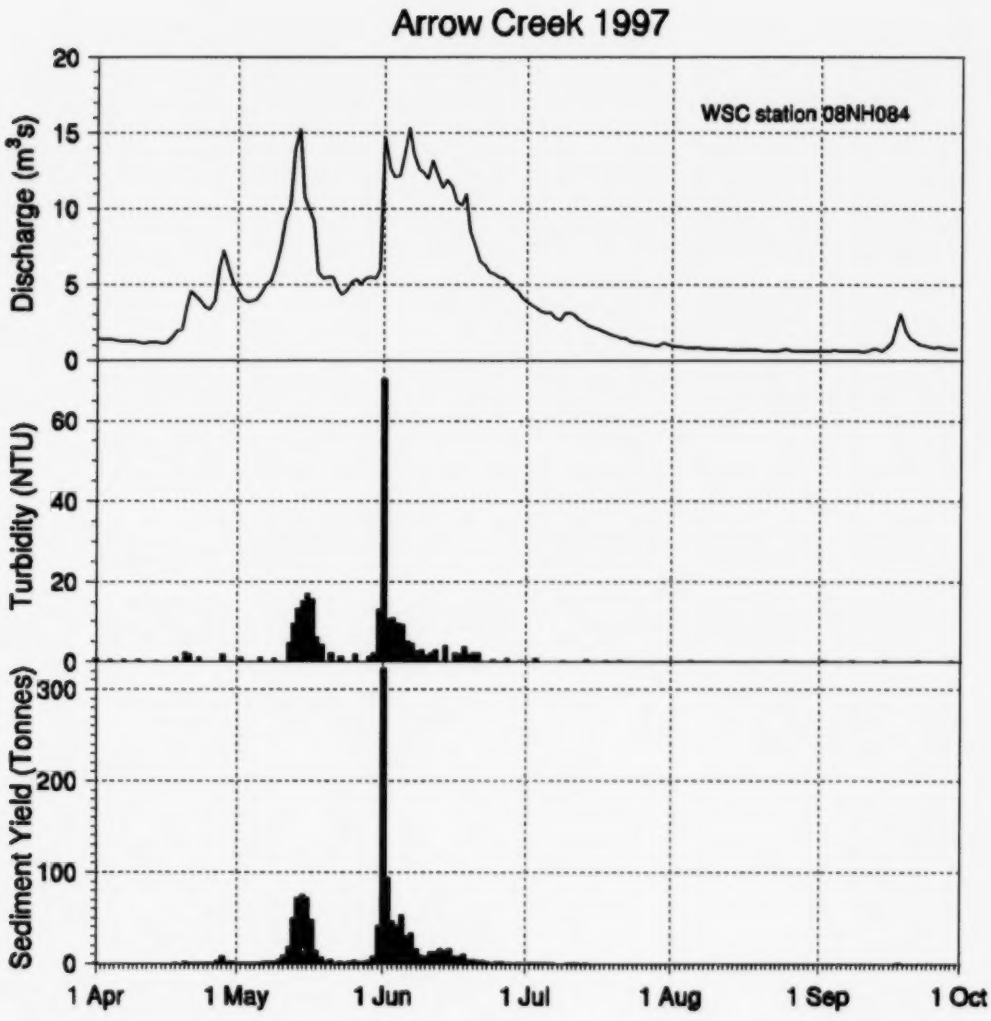

Figure 4. Discharge, turbidity, and calculated sediment yield for Arrow Creek.

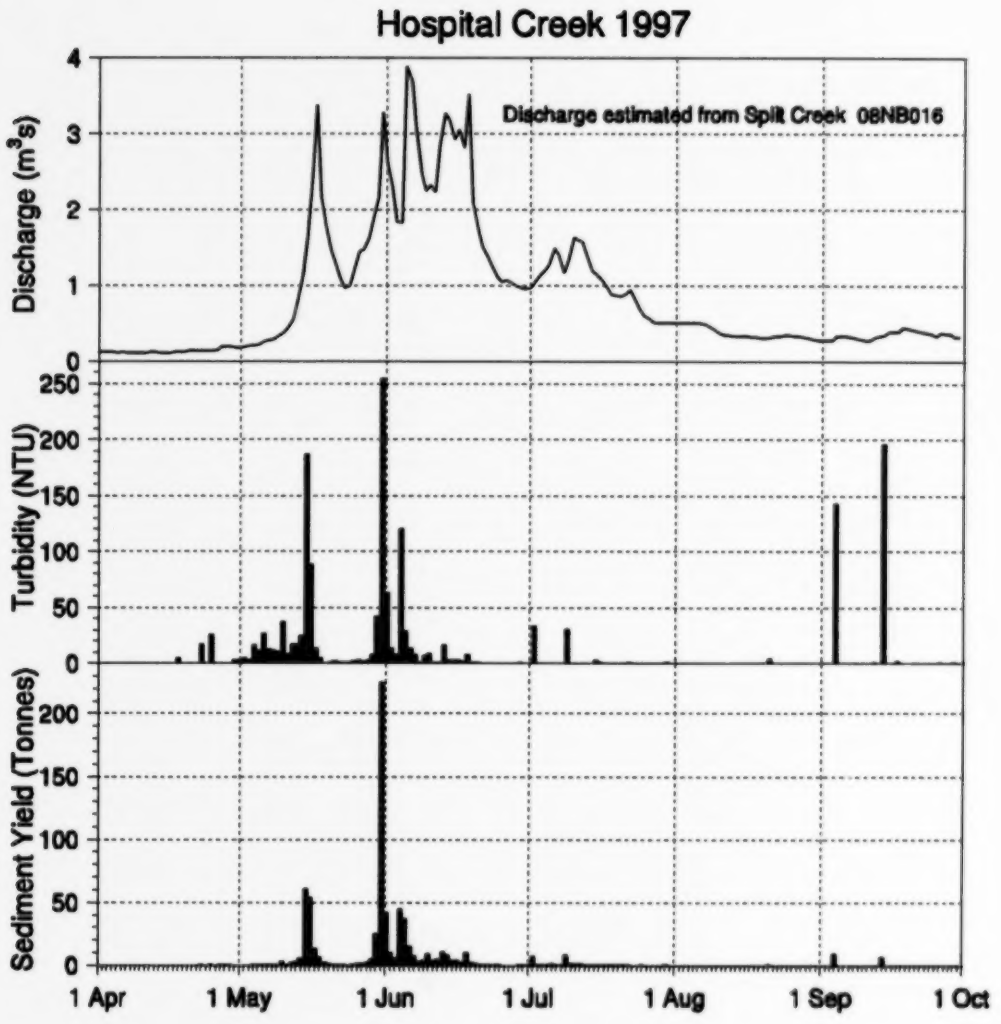

Figure 5. Discharge, turbidity, and calculated sediment yield for Hospital Creek.

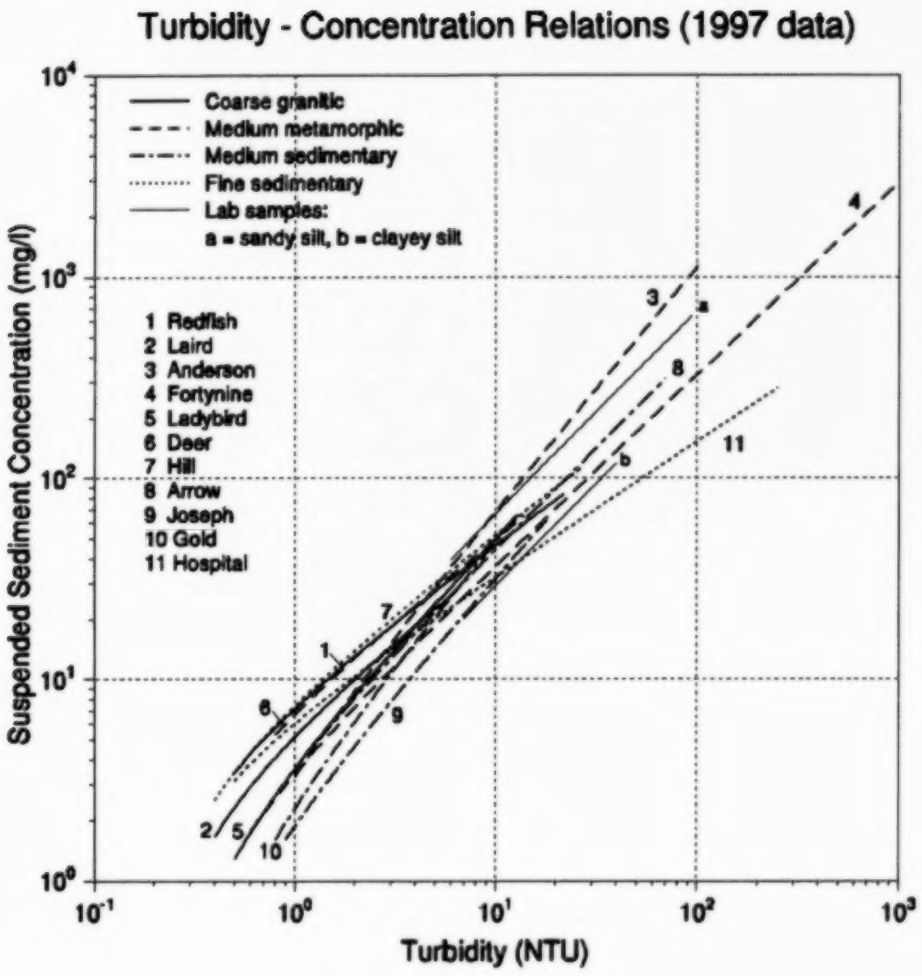

Figure 6. Plot of all regression lines for turbidity-concentration relations, grouped according to watershed geology. The two parallel fine lines are various dilutions of a typical coarse and fine sediment, measured in the lab.

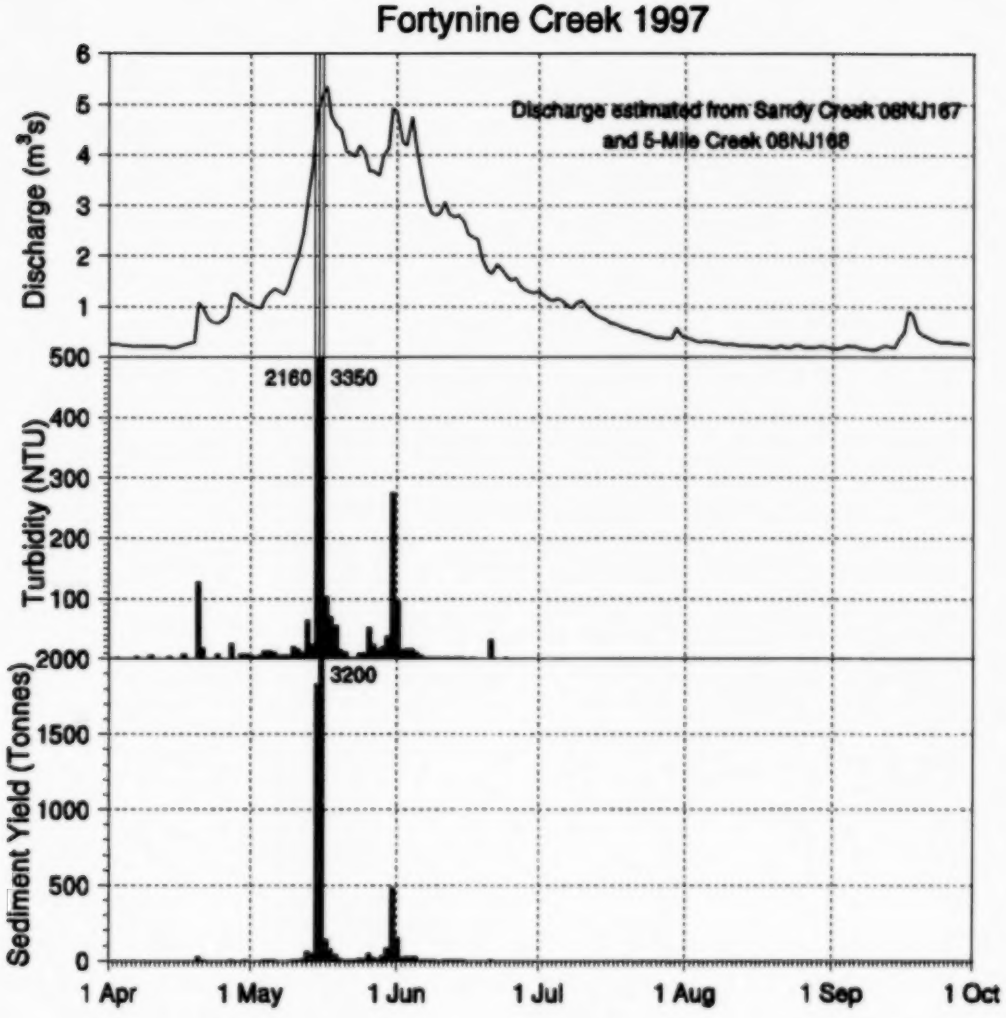

Figure 7. Discharge, turbidity, and calculated sediment yield for Fortynine Creek. (Numbers beside bars indicate values of out-of-range points.)

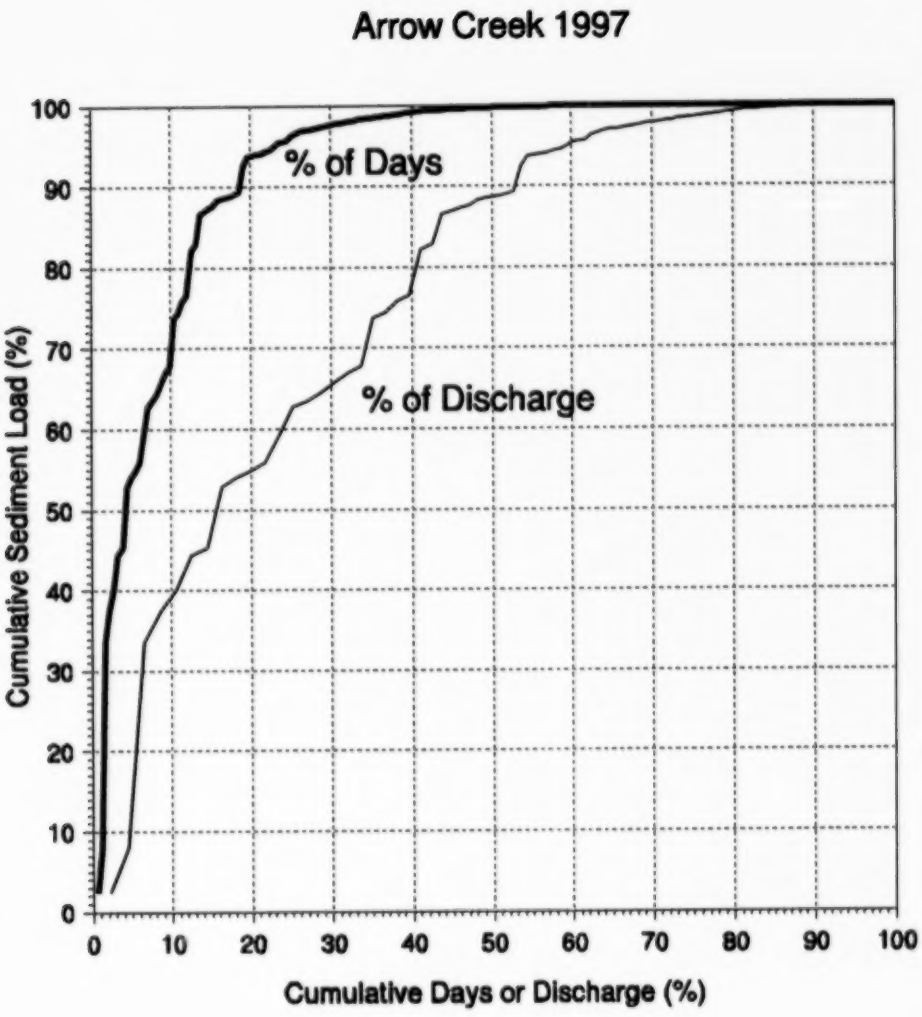

Figure 8. Cumulative curves of sediment load against time and discharge.

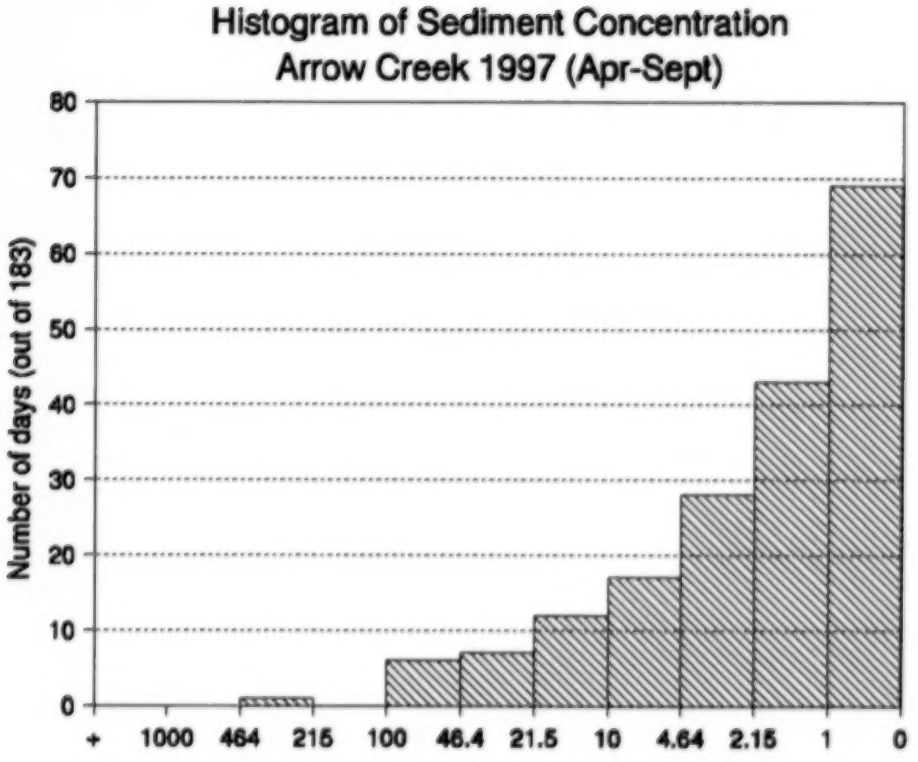

Figure 9. Histogram showing frequency of suspended sediment concentration. The horizontal axis groups concentration measurements according to a geometric series. The data include estimated values.